PO Box 1127
Rotorua 3040
Ph: + 64 7 921 1883
Fax: + 64 7 921 1020
Email: info@ffr.co.nz
Web: www.ffr.co.nz

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Predicting *Pinus Radiata* Productivity from Soil, Climate and Environmental Variables: National and Region Perspectives

Authors:
D Palmer, M Kimberley, and M Watt

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Permanent sample plot data containing soil nutritional information was extracted from a national *Pinus radiata* dataset and used to develop a multiple regression model for the 300 index using independent variables obtained from soil nutrition data, environmental surfaces, and interpolated climate surfaces. The 300 index is defined as the stem volume mean annual increment at age 30 years for a reference regime of 300 stems ha^{-1}. The final dataset consisted of 99 observations distributed fairly evenly across the national *P. radiata* estate. Variables were selected for inclusion in the model using stepwise regression, and the final model accounted for 56% of the variance in the data. The independent variables included in the model were mean minimum annual air temperature, soil carbon to nitrogen ratio, total soil carbon, compound topographic index, and summer fractional available root-zone water storage, with these variables respectively accounting for 39, 9, 3, 3, and 3% of the variance. A one-at-a-time cross validation procedure was used to assess the accuracy of the developed model.

To provide a regional perspective, correlation analysis was undertaken to investigate the significant variables contributing towards productivity within each region. Although the small regional sample sizes influence the correlation between the 300 index and independent variables within each region, the Hawkes Bay (*N*=12), Central Plateau (*N*=30), and the Northland and Waikato regional groupings (*N*=16) showed the most significant correlations. For the Hawkes Bay mean annual minimum air temperature, total phosphorus, and spring solar radiation featured strongly, while a negative relationship with carbon to nitrogen ratio was shown for the Central Plateau. However, out of all the groupings, Northland and Waikato had the strongest relationships with the 300 index. These variables included a positive relationship with total carbon and nitrogen, three variables representing soil water storage, and a negative correlation with the compound topographic wetness index and summer wind speed.

INTRODUCTION

The most widely planted commercial forestry crop in New Zealand (NZFOA, 2005) and the Southern Hemisphere (Lewis and Ferguson, 1993) is *Pinus radiata* D. Don. Numerous studies have demonstrated the responsiveness of this species to the environment. This variation is readily apparent in New Zealand, where volume at age 30 has been found to vary ten-fold across the environmental range (Watt *et al*., submitted). Given this variation, and the reliance of the forestry sector on *P*. *radiata*, the development of maps that can describe fine-scale spatial variation in productivity across broad environmental gradients would be very useful for siting and managing the species.

Considerable research has been undertaken to identify the key determinants of productivity in *P. radiata*. Since the early 1970s many studies covering wide spatial extents have investigated how climate and edaphic properties influence *P. radiata* forest productivity in New Zealand (Jackson and Gilford, 1974; Hunter and Gibson, 1984; Woollons *et al*., 2002; Watt *et al*., 2005, 2008), Chile (Schlatter and Gerding, 1984), Spain (Sánchez-Rodríguez *et al*., 2002; Romanyà and Vallejo, 2004), and Australasia (Czarnowski *et al*., 1971). Almost all of these studies have utilised multiple regression models to predict productivity, with varying degrees of success.

One of the major limitations of these previous models is that thematic spatial representation is not possible, as the dependent variables from which predictions are made are available only as point estimates. However, given the recent proliferation of spatial surfaces describing a diverse range of environmental variables (e.g., Leathwick *et a*l., 2002a, b, 2003; Tait *et al*., 2006), development of such spatial models is now possible. Recent research has shown this method to provide a robust and accurate means of predicting productivity in *Cupressus lusitanica* Mill. (Watt *et al*., 2009). From a management perspective these spatial models represent a major advance, as the maps provide very detailed information of how productivity varies at a relatively fine resolution across the landscape.

From a modelling perspective, soil nutrition is considered important in the determination of site productivity (Watt *et al*., 2008). However, with a few exceptions (e.g., Hunter and Gibson, 1984; Watt *et al*., 2008), little research has investigated the influence of soil nutrition on productivity at a national level. One of the key reasons for this is that spatial estimates of soil nutrition are sparse and often indirect. Indirect measures of soil fertility include subsoil acid-soluble phosphorus (Leathwick *et al*., 2003), land use classification (Ministry of Works and Development, 1979; Newsome *et al*., 2000), and vegetative land cover (Newsome 1987), which respectively estimate or reflect weatherable phosphorus, intensity of land use, and previous land cover. Another limitation of these indirect estimations of soil fertility is that they are all categorical datasets that cannot account for subtle variations in soil fertility within New Zealand (see Watt *et al*., 2008) that are better accommodated using continuous variables.

Development of additional layers more directly describing soil nutrition would be useful. However, as this is a costly and difficult process, it would be useful if the key nutritional determinants of productivity could first be identified. Previous research has shown C:N ratio and total phosphorus to be the most important factors in a national *P. radiata* trial series where trees were grown at extremely high densities, to compress the rotation length (Watt *et al*., 2008). Further research is needed to determine if these two edaphic properties are also important determinants of productivity in stands grown at operational stockings over conventional rotation lengths.

Using the 300 index values derived from a permanent sample plot (PSP) database, the objectives of this study are to (i) develop productivity models by correlation with data derived from soil nutritional data, national extent ancillary maps, and interpolated surfaces using a multiple regression approach, (ii) determine the drivers of *P. radiata* productivity across national and regional extents, and (iii) undertake an assessment of future sampling strategies for soil nutrition at existing PSP locations.

METHODS

Data acquisition and preliminary screening

Pinus radiata permanent sample plot (PSP) data (Ellis and Hayes 1997) were extracted from the New Zealand Forest Research Institute Permanent Sample Plot system (Pilaar and Dunlop, 1990). Previous work (Palmer 2008) found a general increase in the 300 index with year of stand establishment, with stands established in the 1930s being typically ~25% lower than those established in the 1980s, while site productivity indices derived from trees younger than seven years of age were unreliable. As a result we excluded PSP data obtained from stands established prior to 1974 and those stands younger than seven years. Permanent sample plots with plot history data inadequate for accurately estimating the 300 index were also excluded. Remaining plot data were averaged to a 100 m^2 grid to align with the resolution of the environmental information leaving a total of 99 locations available for modelling. The final data covers a wide environmental range across New Zealand and observations are limited only in the lower North Island and the West Coast of the South Island regions (Fig. 1).

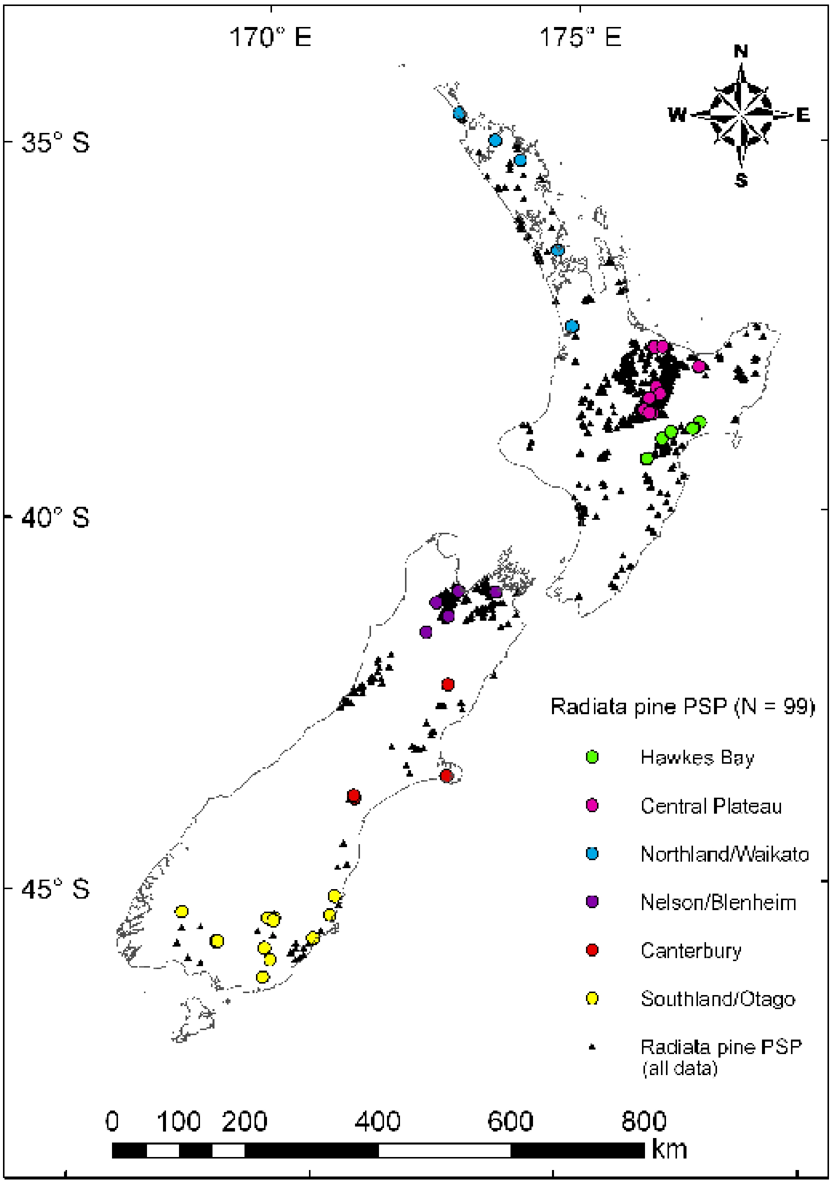

Figure 1. Map of New Zealand showing the location, by region, of the 99 permanent sample plots used in this study. Also shown are the locations of the ~1,764 permanent sample plots used by Palmer (2008).

Tree dimensions

The productivity indices were calculated for the 99 locations using the procedure described by Kimberley *et al.* (2005). To calculate site index, a national height/age model (an equation for predicting height for any age and site index) was used. By inverting the equation, it is possible to obtain Site Index as a function of age and mean top height. In our study, the measurement closest to age 20 years was used for each PSP. Estimation of the 300 index is more complex as, unlike height, stem volume is strongly influenced by stocking and, to a lesser extent, thinning and pruning history. To calculate the 300 index, a plot measurement consisting of the basal area, mean top height and stocking at a known age (again, the measurement closest to age 20 years was used for each PSP in this study), along with stand history information detailing the initial stocking, timing and extent of thinnings, and timing and height of prunings, is required. The 300 index estimation procedure utilised the 300 Index model, an empirical growth model that is sensitive to all the above inputs, and which was calibrated to a site by the 300 index, effectively a local site productivity parameter. An iterative procedure was used to determine the 300 index parameter value consistent with the plot measurement.

Soil variables

For each PSP, forty soil cores were taken from the upper 50 mm of mineral soil. These were bulked to provide a single soil sample for each PSP. Soil samples were air-dried and passed through a 2-mm sieve, then weighed and analysed. Carbon and nitrogen were analysed on a LECO CNS-2000 (Modified Dumas). The LECO CNS-2000 is a non-dispersive, infra-red micro computer based instrument, designed to measure carbon and nitrogen and sulphur content in a wide variety of solid compounds and substances. Total phosphorus was determined using the Kjeldahl digestion method. For details refer to Blakemore *et al*. (1977) and Taylor (2000).

Independent variables

Spatial datasets used to model the 300 index included a wide range of environmental, biophysical, and climatic data, supplemented with the soil variables described above. The final model used the climate variable mean annual minimum air temperature, the soil variables total carbon and carbon to nitrogen ratio, summer fractional available root-zone water storage, and a compound topographic index. Independent data were extracted from these datasets for each of the permanent sample plot locations. For a list of the main independent variables considered for modelling refer to Table 4.

Data analysis

Multiple regression models were constructed using the stepwise regression procedure PROC REG in SAS (SAS Institute, 2000). Variables are added one at time to the model, with the most significant remaining variable being selected for inclusion at each step. Only variables significant at the P=0.05 level were included in the model. The stepwise procedure also tests all the variables already included in the model at each step, and removes any variable that has fallen below the P=0.05 threshold. The stepwise process ends when none of the variables outside the model has an F statistic significant at P=0.05 and every variable in the model is statistically significant at the P=0.05 level.

Because the stepwise procedure does not account for redundancy among variables, initially an analysis was undertaken to determine variables with the greatest correlations to the dependent variable. Among groups of variables found to have multicolinearity, the single variable with the highest correlation coefficient (r) was chosen for potential inclusion in the model. Experience from previous modelling (Palmer 2008, Watt *et al*., 2008) has shown air temperature to be highly correlated to forest productivity. We therefore chose to force the temperature variable with the highest correlation with the 300 index (mean annual minimum air temperature) and its quadratic term into each model. The remaining variables were then tested for inclusion in the model using the stepwise procedure. Predicted values for the 300 index were plotted against their respective actual values to assess bias (Fig. 2). Model accuracy was examined using the coefficient of determination (R^2) between predicted values and the actual 300 index.

A one-at-a-time cross validation was undertaken to assess the final model. The cross validation process excluded the first plot and fitted a model using the stepwise procedure over the remaining sites. This process was iterated with the removal of each site, generating 99 stepwise regression models. The Root Mean Square Error (RMSE) statistic was calculated from this one-at-a-time cross validation.

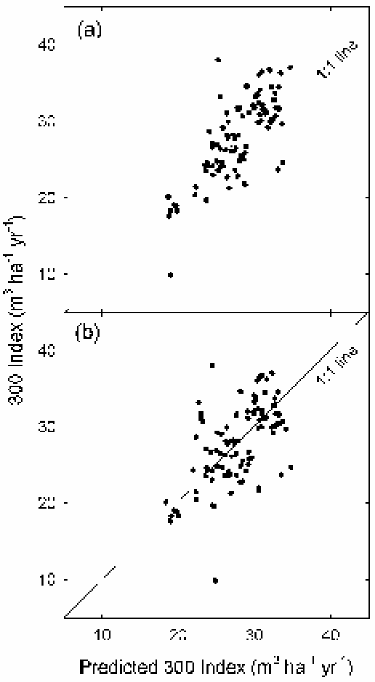

Figure 2. Relationship between predicted and actual 300 index for (a) the fitting and (b) validation datasets.

Assessing PSP gaps related to soil variables

To improve future predictions of productivity models, the collection of representative soil samples is required. To determine where future efforts should be made for the collection of soil samples under *P. radiata*, ~1764 PSP data from Palmer (2008) were compared to data from this work (*N*=99). To provide an overall view of the environmental and climate sampling space, data were extracted for New Zealand Soil Order (Newsome *et al*., 2000), LENZ class (Leathwick *et al*., 2003), mean annual average and minimum air temperatures (Mitchell, 1991; Leathwick *et al*., 2002a; Tait *et al*., 2006), and January fractional available root-zone water storage (Palmer *et al*., 2009) for the complete PSP database (*N*=~1764) and data from this study (*N*=99, containing soil data).

RESULTS

Summary statistics and 300 index model

Rainfall ranged four-fold across sites from 576 to 2,124 mm yr^{-1}. Mean annual air temperature and mean daily solar radiation also varied substantially across sites, ranging from 8.4 to 15.9 ^{o}C and 12.1 to 15.3 MJ m^{-2} day^{-1}, respectively (Table 1). The final 300 index model included mean annual minimum air temperature (T_{min}), carbon to nitrogen ratio (CN_{ratio}), total carbon (C), compound topographic index (CTI), and fractional available root-zone water storage for summer (W_f). The final model formulated using these variables accounted for 56% of the variance in the 300 index. The variable T_{min} was fitted as a downward-facing parabola that reached an asymptote at a T_{min} of 7.7^{o}C. The terms T_{min} and CN_{ratio} were both highly significant (P<0.001) with partial R^2 values of 0.39 and 0.09 respectively. All other model-independent variables were statistically significant at P<0.05 (Table 2).

Table 1. Range in mean annual air temperature, mean daily solar radiation, and total annual rainfall for the permanent sample plots (N=99).

Variable	*Range*
Mean annual air temperature (^{o}C)	8.4-15.9
Solar radiation (MJ m^{-2} day^{-1})	12.1-15.3
Rainfall (mm year^{-1})	576-2,124

Table 2. Summary of statistics for the final predictive models of the 300 index for *Pinus radiata*. Parameter values and variable partial R^2 and cumulative R^2 values (in brackets) are shown. For the significance category the F values and P categories from a F-test, are shown, with asterisks **, * represent significance at P < 0.01, and 0.05.

Equation: $300\ Index = a + bT_{min} + cT_{min}^2 + dCN_{ratio} + eC + fCTI + gW_f$

Para.	Estimate	Variable	Units	Partial and overall R^2	Signif.
a	16.269				
b	4.528	Mean annual minimum air temperature (T_{min})	^{o}C	0.39 (0.39)	30.4**
c	-0.293	T_{min}^2			
d	-0.284	Carbon to nitrogen ratio (CN_{ratio})	-	0.09 (0.47)	15.6**
e	0.376	Total carbon (C)	%	0.03 (0.51)	6.3*
f	-0.747	Compound topographic index (CTI)	-	0.03 (0.53)	5.1*
g	0.068	Summer fractional available root-zone water storage (W_f)	-	0.03 (0.56)	6.2*

Residuals for the final 300 index model were normally distributed and exhibited little apparent bias with predicted values (Fig. 3a). Residuals also exhibited little apparent bias with independent variables used in the 300 index model (Figs. 3b-f).

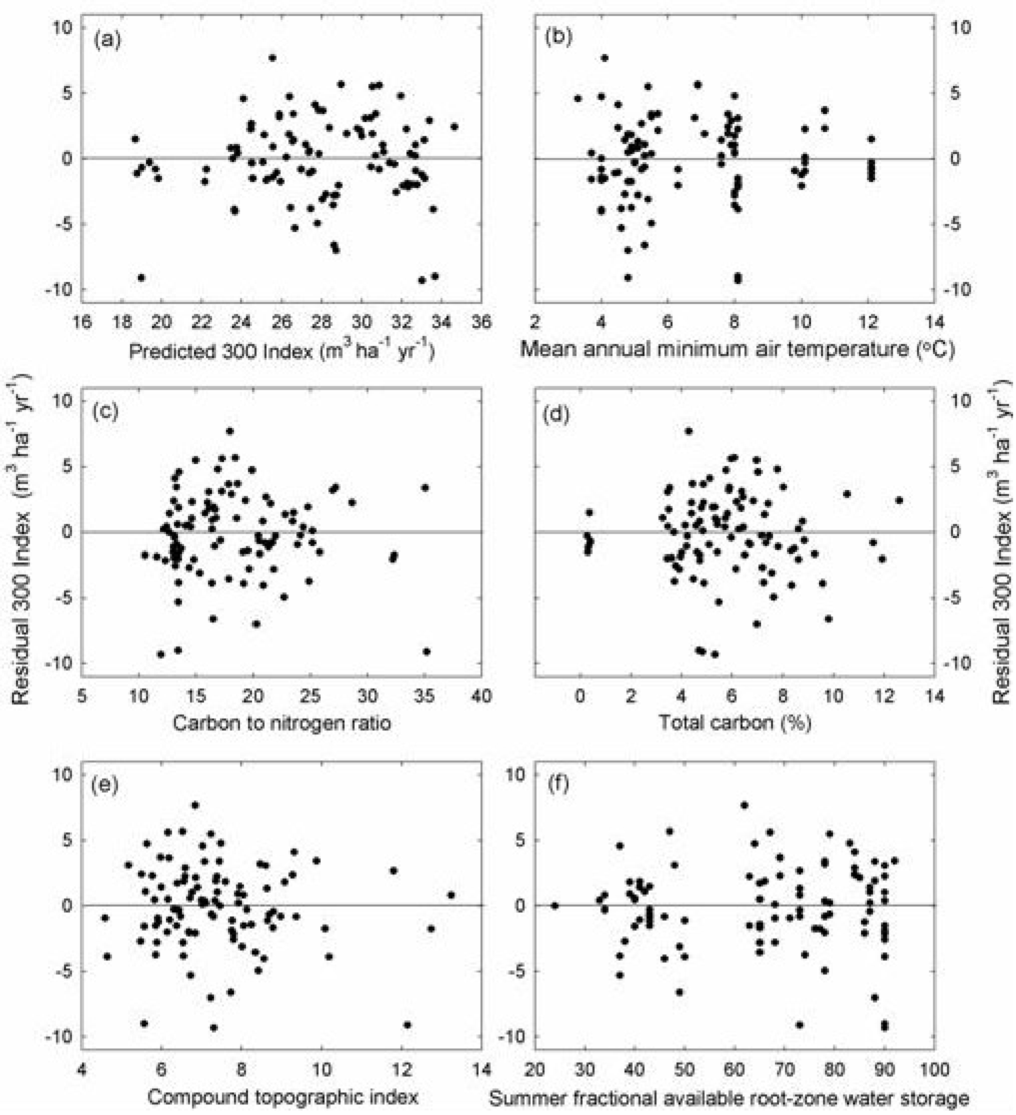

Figure 3. Plot of residual values against (a) predicted 300 index, (b) mean annual minimum air temperature, (c) carbon to nitrogen ratio, (d) total carbon, (e) compound topographic index, and (f) summer fractional available root-zone water storage.

Although the final 300 index stepwise regression model provides an R^2 of 0.56, one-at-a-time cross validation provided a substantially lower validation R^2 of 0.33. The root mean square error statistic (RMSE) for the fitted 300 index final model is 3.54 m^3 ha^{-1} yr^{-1}, while the RMSE from cross validation is 4.34 m^3 ha^{-1} yr^{-1} (Table 3).

Table 3. Coefficient of determination and root mean square error statistics from the final stepwise regression 300 index model (*N*=99), and one-at-a-time cross validation using stepwise regression.

Model	R^2	*RMSE*
Statistics from final stepwise regression	0.56	3.54
Cross validation statistics from one-at-a-time stepwise regression	0.33	4.34

To assess the functional forms of the independent variables, partial response curves were generated for the 300 index model (Fig. 4). The 300 index and mean annual minimum air temperature was modelled as a downward facing parabola, with an optima reached at 7.7°C (Fig. 4a). The 300 index exhibited a negative linear relationship with carbon to nitrogen ratio (Fig. 4b) and compound topographic index (Fig. 4d). Partial response curves for the 300 index show a linear and positive relationship with both total carbon (Fig. 4c) and summer fractional available root-zone water storage (Fig. 4e).

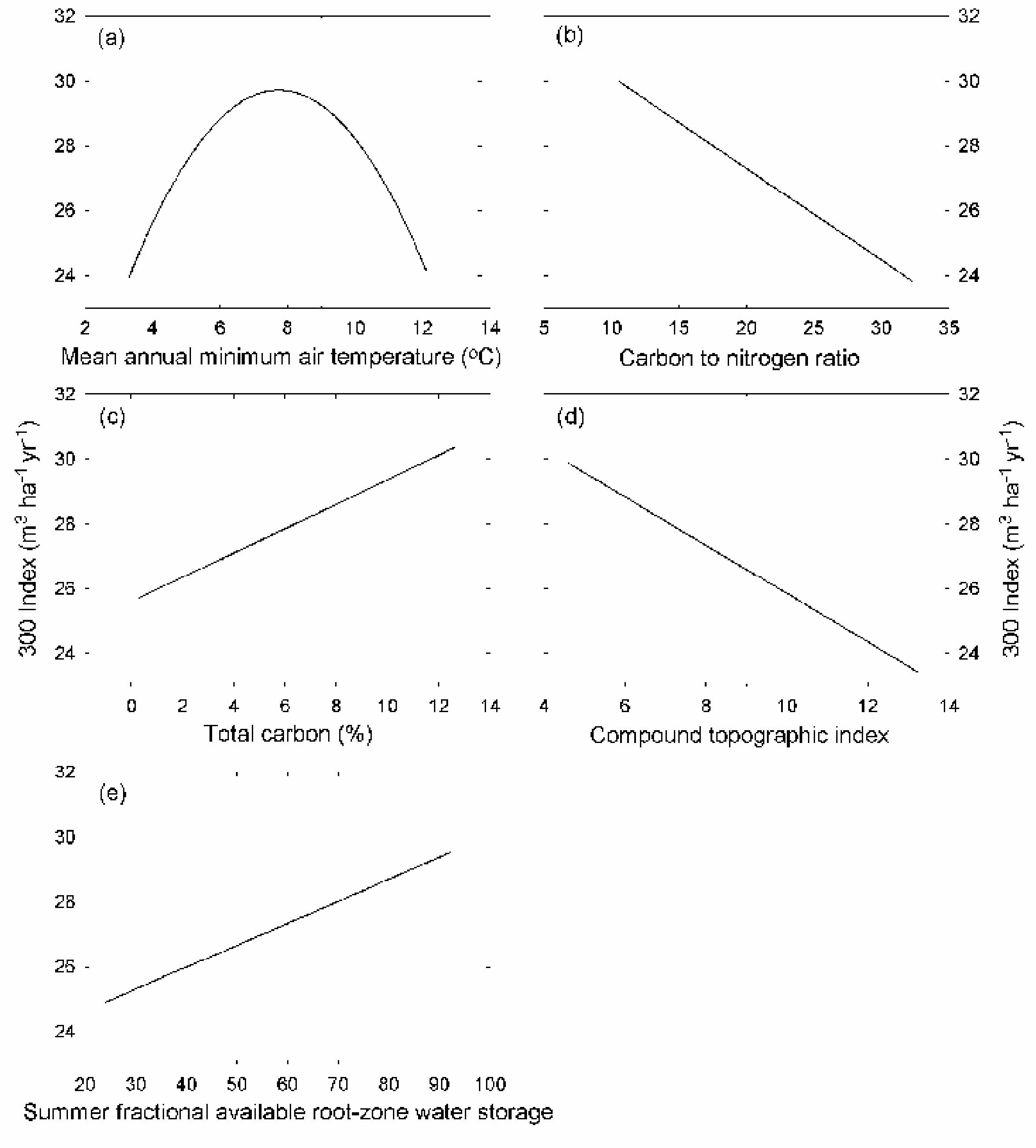

Figure 4. Partial response curves of 300 index plotted against (a) mean annual minimum air temperature, (b) carbon to nitrogen ratio, (c) total carbon, (d) compound topographic index, and (e) fractional available root-zone water storage for summer.

Regional correlations between 300 index and independent variables

To assess relationships between the 300 index and soil nutritional, environmental, and climate variables at a regional level, correlation analysis (*r*) was undertaken within each region (Table 4). The Hawkes Bay region (*N*=12) exhibited moderate positive correlations (*R*>0.6) between the 300 index and mean annual minimum air temperature, total phosphorus, and spring solar radiation. For this region the 300 index was also positively correlated with growing degree days above 5°C, and June solar radiation. Negative correlations were found between the 300 index and both summer wind speed and elevation.

For the Central Plateau (*N*=30), the 300 index has was most closely related to carbon to nitrogen ratio through a negative linear correlation. There are a number of other variables significantly correlated with the 300 index, including mean annual minimum temperature, total nitrogen, elevation, compound topographic index, growing degree days above 5°C, number of days ground frost, spring and June solar radiation, potential rooting depth, and summer fractional available root-zone water storage (See Table 4 for +ve/-ve correlations and level of statistical significance).

For the Northland and Waikato regional grouping (*N*=16), the 300 index has very strong positive correlations of high statistical significance with available water capacity, summer fractional available root-zone water storage, total carbon, carbon to nitrogen ratio, slope, and monthly water balance. Very strong negative correlations were found between the 300 index and compound topographic index, summer wind speed, and annual water deficit.

For the Canterbury region (*N*=7) the 300 index exhibited strong negative correlations that were moderately significant with compound topographic index and number of days ground frost. Although the small number of locations in the Nelson and Blenheim regional grouping (*N*=9) and the Southland and Otago grouping (*N*=25) displayed no statistically significant relationships with the 300 index, a number of variables exhibited strong correlations.

Table 4. Summary statistics for the relationship between the 300 index and independent variables for the six regional locations across New Zealand. For the level of significance *P* categories are shown, with asterisks **, and * representing significance at $P < 0.01$, and 0.05. See Fig. 1 for PSP locations within regions. For the variables shown here refer to the variable selection process in Section 2.5.

		Hawkes Bay		Central Plateau		Northland and Waikato		Nelson and Blenheim		Canterbury		Southland and Otago	
		N=12		*N*=30		*N*=16		*N*=9		*N*=7		*N*=25	
Variable	Unit	*R*	*P*	*R*	*P*	*R*	*P*	*R*	*P*	*R*	*P*	*R*	*P*
Mean annual minimum air temperature	^{0}C	0.71	**	0.42	*	-0.88’	ns	0.66	ns	0.63	ns	0.13	ns
Total carbon	%	0.34	ns	-0.09’	ns	0.92	**	0.18	ns	-0.73’	ns	-0.35’	ns
Total nitrogen	%	0.47	ns	0.40	*	0.87	**	0.25	ns	-0.33’	ns	-0.10’	ns
Total phosphorus	mg/kg	0.77	**	0.23	ns	0.47	ns	-0.07’	ns	-0.82’	*	-0.17’	ns
Carbon/nitrogen ratio	-	-0.44	ns	-0.56	**	-0.53	*	-0.22	ns	-0.34	ns	-0.35	ns
Elevation	m	-0.60	*	-0.45	*	0.40’	ns	-0.32	ns	-0.54	ns	-0.27	ns
Length and slope factor	-	0.17’	ns	0.04’	ns	0.53’	*	-0.07	ns	0.47’	ns	-0.16	ns
Slope	%	0.35’	ns	0.09’	ns	0.78’	**	-0.12	ns	0.74’	ns	-0.06	ns
Compound topographic index	-	-0.16	ns	-0.40	*	-0.88	**	-0.27	ns	-0.87	*	-0.01	ns
Growing degree days above 5^{0} C	Degree days above 5^{0}C	0.62	*	0.44	*	-0.87’	ns	0.39	ns	0.28	ns	0.25	ns
Monthly mean number of days ground frost	days	-0.55	ns	-0.42	*	-	ns	-0.25	ns	-0.77	*	-0.07	ns
Spring solar radiation	Mj m^{-2} day^{-1}	0.75	**	0.43	*	-0.59’	ns	0.48	ns	-0.43’	ns	-0.04’	ns
Annual water deficit	mm	0.10	ns	-0.18	ns	-0.81	**	0.47	ns	0.24	ns	-0.20	ns
June solar radiation	Mj m^{-2} day^{-1}	0.67	*	0.39	*	-0.84’	ns	0.52	ns	0.28	ns	-0.17’	ns
Monthly water balance ratio	-	-0.15	ns	0.13	ns	0.78	**	-0.17	ns	-0.55	ns	0.26	ns
Summer fractional available root-zone water storage	-	-0.04’	ns	0.44	*	0.92	**	-0.09’	ns	0.45	ns	0.39	ns
Available water capacity	%	-0.09’	ns	-0.17’	ns	0.93	**	0.28	ns	-0.64’	ns	0.24	ns
Potential rooting depth	m	0.42	ns	0.36	*	-0.72’	ns	0.30	ns	0.70	ns	-0.20’	ns
Summer wind speed	km hr^{-1}	-0.68	*	-0.29	ns	-0.85	**	0.37’	ns	0.89’	ns	-0.03	ns

‘ prime is used where the correlation sign is considered inverse (incorrect)
Note: the independent variables shown in this table are a subset of around 200 available variables – refer to Section 2.5 for the variable selection process

Identifying missing data within independent variable space across PSPs containing soil nutritional information

New Zealand Soil Orders are generally well represented in the complete PSP database for *P. radiata,* with only Anthropic, Granular, Organic, Semiarid, and Oxidic Soil Orders under-represented or missing. These same Soil Orders were also under-represented for the PSP locations in this study, but extended to Gley, Allophanic, Raw, and Podzol soils (Table 5).

The majority of the LENZ classes are represented for the complete PSP database with the expected exclusion of the Southern Alps, ultramafic soils, and permanent snow and ice where forests are generally not grown. However, there are only three observations for the central poorly drained recent soils and the western South Island recent soils. These same classes are missing for PSP data used in this study. Other classes completely missing from this study's dataset were the western and southern North Island lowlands, central well-drained recent soils, central upland recent soils, and the western South Island foothills and Stewart Island (Table 6).

The complete PSP database for *P. radiata* shows that fractional available root-zone water storage, mean annual air temperatures, and mean annual minimum air temperatures are reasonably well represented across their respective data ranges. However, for the data used in this study the classes 20-25, 50-55, and 95-100 were under-represented or missing from the fractional available root-zone water storage (Table 7). For mean annual and mean minimum air temperatures the 7 to 8 °C class (Table 8) and the 11 to 12 °C class (Table 9), respectively, were not represented.

Table 5. Number of Permanent Sample Plots from the complete database (*N*=~1764) and from this study (*N*=99) representing Soil Order.

	PSP observations for *Pinus radiata*	
Soil Order	Complete database	Containing soil data
Anthropic	2	-
Brown	443	18
Melanic	24	5
Gley	22	1
Allophanic	53	-
Pumice	530	38
Granular	1	-
Organic	3	-
Pallic	202	16
Recent	227	10
Semiarid	-	-
Ultic	72	11
Raw	57	-
Oxidic	-	-
Podzol	122	-

Table 6. Number of Permanent Sample Plots from the complete database (*N*=~1764) and from this study (*N*=99) representing LENZ class.

LENZ class	PSP observations for *Pinus radiata*	
	Complete database	Containing soil data
A: Northern lowlands	80	8
B: Central dry lowlands	138	6
C: Western & southern Nth Is. lowlands	21	-
D: Northern hill country	139	5
E: Central dry foothills	101	1
F: Central hill country: volcanic plateau	699	37
G: Northern recent soils	112	6
H: Central sandy recent soils	50	3
I: Central poorly drained recent soils	3	-
J: Central well-drained recent soils	43	-
K: Central upland recent soils	5	-
L: Southern lowlands	28	5
M: Western Sth Is. recent soils	3	-
N: Eastern Sth Is. plains	61	3
O: Western Sth Is. foothills and Stewart Is.	45	-
P: Central mountains	94	5
Q: Southeastern hill country & mountains	141	20
R: Southern Alps	-	-
S: Ultramafic soils	-	-
T: Permanent snow and ice	-	-

Table 7. Number of Permanent Sample Plots from the complete database (*N*=~1764) and from this study (*N*=99) representing fractional available root-zone water storage.

Fractional available root-zone water storage	PSP observations for *Pinus radiata*	
	Complete database	Containing soil data
20-25	8	1
25-30	65	-
30-35	72	5
35-40	119	9
40-45	90	9
45-50	62	6
50-55	86	1
55-60	91	2
60-65	96	9
65-70	92	5
70-75	112	4
75-80	125	14
80-85	180	25
85-90	255	4
90-95	226	5
95-100	22	-

Table 8. Number of Permanent Sample Plots from the complete database (*N*=~1764) and from this study (*N*=99) representing mean annual air temperature.

Mean annual temperature (°C)	PSP observations for *Pinus radiata*	
	Complete database	Containing soil data
7 - 8	8	-
8 - 9	59	6
9 - 10	296	36
10 - 11	295	7
11 - 12	379	8
12 - 13	337	10
13 - 14	226	18
14 - 15	128	6
15 - 16	35	8

Table 9. Number of Permanent Sample Plots from the complete database (*N*=~1764) and from this study (*N*=99) representing mean annual minimum air temperature.

Mean minimum annual temperature (°C)	PSP observations for *Pinus radiata*	
	Complete database	Containing soil data
3 - 4	59	10
4 - 5	243	24
5 - 6	416	17
6 - 7	349	5
7 - 8	319	17
8 - 9	140	10
9 - 10	100	3
10 - 11	103	7
11 - 12	8	-
12 - 13	26	6

DISCUSSION

Modelling 300 index nationally using climate, soil, and environmental data

The productivity model developed here considerably advances our understanding of how soil nutrition, climate and environment regulate the productivity of *Pinus radiata*. This study clearly highlights the importance of temperature and carbon to nitrogen ratio as the main determinants of productivity for this species, accounting for 39 % and 9 % of the variance in the 300 index respectively. Total carbon, compound topographic index, and summer fractional available root-zone water storage each explain 3 % of the variance in productivity nationally (Table 2).

The dominance of air temperature as the main driving variable remains sound from a physiological viewpoint, and is consistent with productivity models developed for other plantation species (Palmer 2008; Watt *et al*., 2009). The use of soil nutritional data is also consistent with other New Zealand productivity studies (Watt *et al*., 2005; 2008) showing that productivity increases with increasing soil carbon and decreasing carbon to nitrogen ratio. Partial response curves (Figure 4b) highlight the substantial influence the carbon to nitrogen ratio has on *P. radiata* productivity, increasing ~6 m^3 h^{-1} yr^{-1} across the data range of this study. This finding highlights the importance of soil nutrition in *P. radiata* productivity across New Zealand.

Soil water balance has long been recognised as a major determinant of *P. radiata* growth at specific locations exhibiting seasonal water deficits (McMurtrie *et al*., 1990; Arneth *et al*., 1998a, 1998b; Richardson *et al*., 2002; Watt et *al*., 2003). As a result root-zone water storage, expressed as a fraction of the maximum available, has often been utilised as a growth modifier in both process-based (Landsberg and Waring, 1997) and hybrid growth models (Watt *et al*., submitted). Nevertheless, very few national or regional management models use this variable in a predictive capacity. Our research clearly demonstrates the use of average summer W_f as a significant determinant of productivity. This finding also endorses the use of national scale water balance models, such as Swatbal (Palmer *et al*., 2009), in providing estimates of W_f at a fine scale that can be used as input into management models such as those developed in this paper.

The compound topographic index (CTI), commonly called the topographic wetness index, is extensively used to “describe the effects of topography on the location and size of saturated source areas of runoff generation” (Wilson and Gallant, 2000). The CTI is useful in capturing information related to the distribution and abundance of water, depth of water table, evapotranspiration, susceptibility of soils to erosion, and soil horizon thicknesses. These features in turn influence the spatial patterns of native vegetation and pedogenic processes. CTI is commonly used in hydrological, geomorphological, pedological, and ecological applications. Quinn *et al*. (1995) described how the steady-state CTI could be used effectively in the TOPMODEL hydrologic modelling structure as well as highlighting the various problems associated with use and application of CTI models.

The compound topographic index takes the form:

$$\text{CTI} = \ln\left(\frac{A_s}{\tan \beta}\right)$$

where A_s is the specific catchment area (m^2 m^{-1}), and β is the slope angle in radians. This form of the topographic wetness index assumes that steady state conditions prevail (Moore *et al*., 1991, 1993; Moore 1996). Compound topographic index values from this study range from 4.6 to 13.2 where values from zero to greater than 20 are typically represented nationally. A value of zero indicates a location where saturation is low, and a value of 20 or more indicates locations were saturation is high. Generally, high saturation values occur in areas where the specific catchment area (A_s) is large (typically convergent areas in the landscape) and slope angle (β) is relatively small. Conversely, low saturation values are found in areas where specific catchment area is small and slope gradient is relatively steep.

The model uses the readily available variables minimum air temperature, soil water balance, and compound topographic index coupled with carbon to nitrogen ratio and total carbon determined from 0 to 50 mm soil samples collected in the field. The purpose of developing this model was to provide managers with an easy-to-use tool capable of estimating *P. radiata* productivity nationally at a forest site of interest. The collection of soil samples to a 50-mm depth saves time and effort compared with sampling to greater depths. Furthermore, this approach requires only the determination of total carbon and nitrogen in the soil laboratory, rather than a suite of individual tests.

The applicability of this model assumes that C:N ratio values are not unduly influenced by afforestation. This is because the soil data collected for this research was from forest sites and not farmland directly. However, in tracking C:N ratios in a number of trials, the only example where the ratio changed significantly during a crop rotation was on a coastal sand site (P. Beets pers. com.), suggesting this model is applicable across the majority of New Zealand environments.

An added strength of this 300 index model is the use of independent variables comprised primarily of continuous data. The limitation of applying categorical variables in the modelling process is that categorical variables cannot account for subtle variations in a variable such as soil fertility (see Watt *et al*., 2008) that can be accommodated using continuous variables. In previous studies (Palmer 2008; Watt *et al.,* in review) categorical variables were relied on to develop the 300 index models and surfaces. The Watt *et al*. (in review) national 300 index model was developed using ~1700 PSP sites, and the independent continuous variables autumn ground frost and mean fractional available root-zone water storage respectively accounted for 14% and 17% of the variance. Categorical environmental variables in the final model increase the variance explained to 53%. The Palmer (2008) partial least squares (PLS) and regression kriging (RK) model developed from the same data set uses numerous climate and environmental variables, explaining 48% and 61% of the variance respectively. A robust validation procedure shows the RMSE to be 4.22 m^3 ha^{-1} yr^{-1} and 3.65 m^3 ha^{-1} yr^{-1}, for PLS and RK, respectively. The RMSE statistics from this study provide similar error estimation with the final model having a RMSE of 3.5 m^3 ha^{-1} yr^{-1} increasing to 4.2 m^3 ha^{-1} yr^{-1} in the cross validation.

From the onset of this research, the choice of an appropriate multiple linear regression model was made by testing different available models. The PLS method is an ideal modelling approach (Palmer 2008) with a robust cross validation method. However, developing a PLS model with a reasonable coefficient of determination and error estimate requires a complex model comprising numerous independent continuous and categorical variables. PLS does not provide the simple, easy-to-apply model required for the purpose of this study. General linear models developed using expert knowledge were also considered, but found to provide inadequate validation methods because of our small sample population (N=99). Stepwise regression provided both a simple easy-to-use model for industry and robust error estimation. However, Table 3 shows a substantial difference (0.2) in the R^2 for the model described in Table 2 compared to the one-at-a-time cross validation. These results are reflected in the RMSE estimates for the model described in Table 2 and the cross validation statistics with RMSE of 3.5 m^3 ha^{-1} yr^{-1} and 4.2 m^3 ha^{-1} yr^{-1}, respectively. This highlights the importance of providing a robust validation process associated with the development of a model.

One-at-a-time cross validation means the development of a model each time we remove one of the 99 sites (dependent variable) used in the final model. This means that independent variables are added or removed depending on their relationships with productivity. This allows a comprehensive validation approach as opposed to running the same model 99 times (removing one site at a time) which tends to provide over-optimistic R^2 and RMSE values. Of the 99 one-at-a-time cross-validation models developed, 63 models have the same variables as described in this paper, 19 models removed the variable carbon, while 12 models added the variable slope, and only 5 models had variations beyond adding or removing one independent variable, suggesting that this model and its form is relatively stable.

Assessing the relationship between 300 index and independent variables regionally

Generally sample numbers were too small for the development of sensible individual regional 300 index models. Correlation analysis was undertaken within the six regional groupings (see Figure 1 for site locations) to highlight the importance of independent variables used in the 300 index national model (see Table 4).

Although sample size plays an important role in the relationship between the 300 index and independent variables, correlation analysis shown in Table 4 highlights a range of environmental and climate data influencing productivity at a regional level. Overall, the Northland and Waikato regional grouping had the strongest correlations with soil nutrition (total carbon and nitrogen), the soil water storage component, and wind speed. Compound topographic index also featured with all correlations above 0.78. Although this was a relatively small dataset (N=16), on closer inspection the data comprises two main soil groups, representing sandy parent materials (Pinaki sand in the far north) and silt loam and clay loams of the Ultic Soil Order. This is logical from a soil fertility perspective, as sandy soil parent materials generally have a low nutrient status compared to the heavier clays of greater relative fertility. Interestingly, these variables perform better independently compared to the national model developed in this paper. However, the development of a regional model from 16 observations must be undertaken with a cautionary note. For the Hawkes Bay, air temperature, total phosphorus, and solar radiation play a role. Overall, the Central Plateau grouping has the greatest number of samples and variables correlated with the 300 index (P<0.05). Of most significance was the carbon to nitrogen ratio, followed by nitrogen, air temperature, number of days frosts, growing degree days, elevation, solar radiation, water storage and rooting depth. These variables are consistent with previous studies (for example, Watt *et al*., 2008).

From a statistical and modelling perspective, the greater the number of samples and the range which they represent the better. Estimating the sample numbers required regionally to develop robust models is not exact. However, we suggest an absolute minimum of 50 samples, but preferably more than 100 samples representing each region, across the range of key climatic and edaphic properties, would be required to develop reasonably robust regional models.

Identifying the gaps within independent variable space across PSPs containing soil nutritional information

Maps (Figure 5) were developed to provide a general overview of the 99 locations from this study in relation to independent variable data gaps identified in Tables 5, 6, 7, and 8. These maps represent (a) New Zealand Soil Orders, (b) Land Environments for New Zealand (LENZ) classes, (c) mean annual temperatures, and (d) mean fractional available root-zone water storage for January.

Generally, air temperatures and soil water storage are well represented across New Zealand, and locating new PSP locations to represent the missing data is a straightforward process. Conversely, there remain some large gaps in the LENZ and soil order classes. Not only are many classes missing, but sample numbers within classes are often low.

Identifying gaps in future datasets should begin with selecting PSPs at geographic regions not represented in this study. For example, the West Coast of the South Island has no samples represented. After choosing PSP locations based on geographic representation, the focus can be narrowed to specific variables that we know to be important to *P. radiata* productivity. Temperature tends to be the outstanding driver of productivity models, although ensuring a good geographic coverage will generally account for this. Temperature extremes could be worth focussing on as the

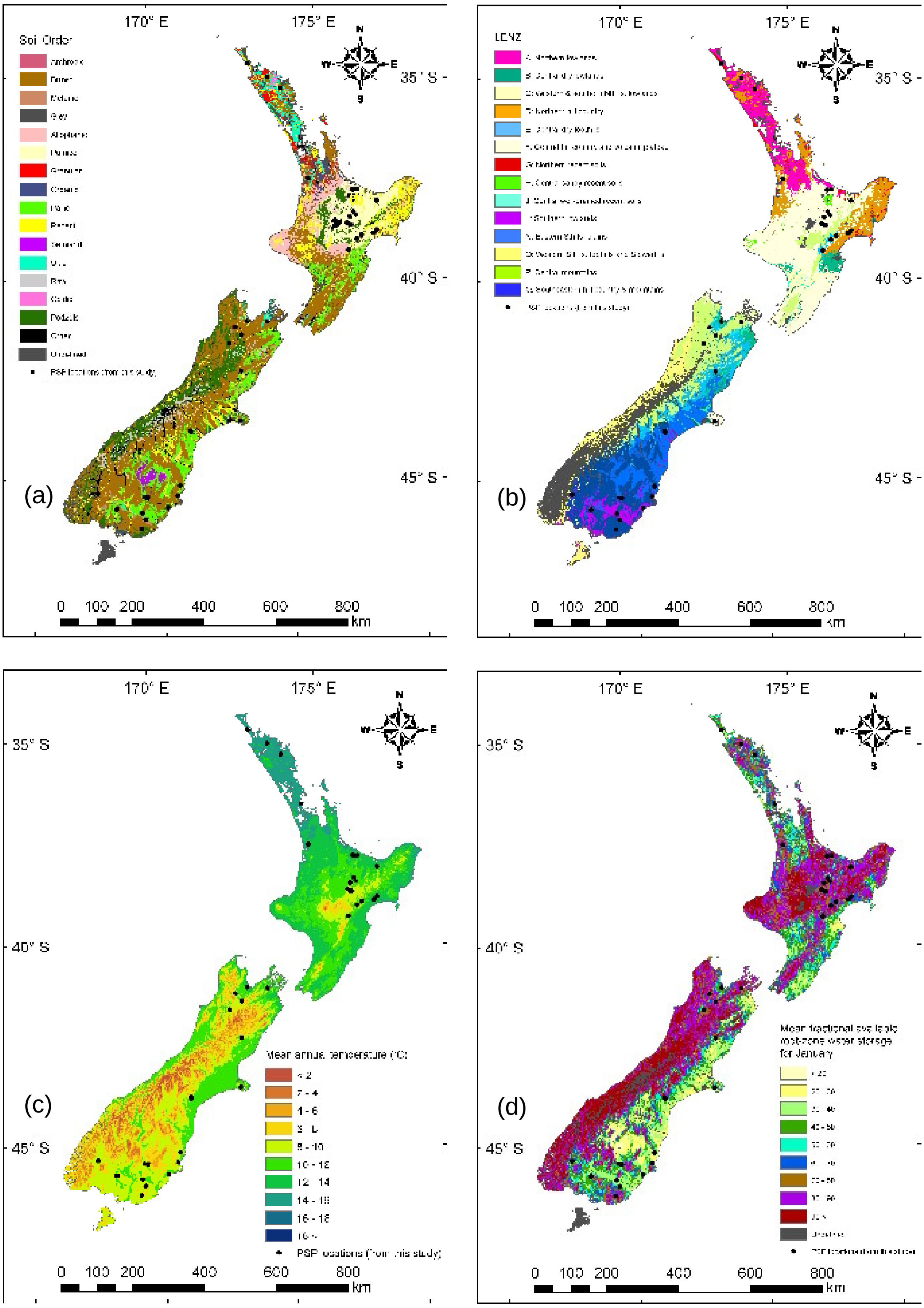

Figure 5. Maps representing (a) New Zealand Soil Orders, (b) classes for New Zealand land environments, (c) mean annual air temperatures, and (d) January mean fractional available root-zone water storage. The 99 PSP locations used in this study are shown as black filled circles.

PSP dataset used in developing the Palmer (2008) models and surfaces had little representation at cooler elevated sites. Soil properties were significant contributors in this study, and therefore selecting PSP locations for future soil samples based on soil groupings should be beneficial. Selection based on LENZ groupings should also be beneficial because LENZ encompasses a range of climatic and environmental properties. Soil water balance should also feature strongly in the selection process.

Before committing ourselves to identifying specific PSP locations where soil samples are required, we need to define what purpose the data is required for. Are we collecting soil samples to develop decision support tools, or do we wish to create productivity surfaces and maps, or is the requirement some combination of these? Also, can we combine these requirements for productivity modelling with other studies - for example, the modelling of wood properties such as wood density or stiffness.

In conclusion, these results highlight the importance of air temperature and carbon to nitrogen ratio as the main drivers in the development of this productivity model. Future models are likely to improve as more samples are collected and as sample numbers become increasingly represented within the different regions. The development of these models will provide invaluable decision support for determining optimal sites for plantation species such as *Pinus radiata*.

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